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41 P

PERFORMANCE ANALYSIS OF HIGH-ENERGY CHEMICAL STAGES FOR INTERPLANETARY MISSIONS.

PART III :

BRAKE TO MARS ORBIT

By

Walter H. Stafford and Carmen R. Catalfamo

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BRAKE TO MARS ORBIT

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ABSTRACT

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The effect of earth thrust-to-weight ratios, and specific impulses on trajectory parameters has been investigated for braking to an orbit about Mars. The thrust vector was directed against the velocity vector in all instances. Specific impulses of 400 to 500 seconds and earth thrust-to-weight ratios of 0.2 to 1.0 were used.

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FLIGHT OPERATIONS SECTION
ADVANCED FLIGHT SYSTEMS BRANCH
PROPULSION AND VEHICLE ENGINEERING DIVISION

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DEFINITION OF SYMBOLS

Symbol	Definition
F	Thrust, kp
F/W_o	Initial thrust-to-weight ratio (based on weight at earth sea level)
f	Stage mass fraction, W_P/W_A
g	Gravitational acceleration, m/sec^2
H	Energy
h	Altitude, km
Δh	Altitude change, $h - h_o$, km
I_{sp}	Specific impulse, sec
m	Mass, $\frac{kp - sec^2}{m}$
r	Radius, km
r_o	$h_o + r_{♂}$, km
t_B	Burning time, sec
V	Velocity
V^*	Comparative velocity
V_1	Stage characteristic velocity
V_∞	Hyperbolic excess velocity
W_A	Stage weight, $W_o - W_L$, kp
W_L	Payload weight, kp
W_o	Gross weight, kp
W_P	Propellant weight, kp
X	Surface range, km
α	Angle of attack (angle between velocity vector and thrust vector), deg
ζ	Propellant mass fraction, W_P/W_o

DEFINITION OF SYMBOLS (Concluded)

Symbol	Definition
ϑ	Flight path angle from vertical, deg
μ	Gravitational constant for Mars, 42930.0 km^3/sec^2
ψ	Central angle, deg
Subscripts	
C	Burnout
ex	Exhaust
f	Final
id	Ideal
K	Circular
o	Initial
P	Propellant
♂	Mars
Abbreviations	
km	Kilometer
kp	Kilopond
m	Meter
sec	Second

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PERFORMANCE ANALYSIS OF HIGH-ENERGY CHEMICAL STAGES FOR INTERPLANETARY MISSIONS

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SUMMARY

The effect of earth thrust-to-weight ratios, and specific impulses on trajectory parameters has been investigated for braking to an orbit about Mars. The thrust vector was directed against the velocity vector in all instances. Specific impulses of 400 to 500 seconds and earth thrust-to-weight ratios of 0.2 to 1.0 were used.

SECTION I. INTRODUCTION

A study of trajectory requirements is of fundamental importance in planning the exploration of Mars. Preliminary analysis of Martian missions requires a rapid method of sufficient accuracy for determining trajectory parameters.

The purpose of this study is to present a method for determining the trajectory parameter for powered braking into an orbit about Mars when the hyperbolic excess velocity is known.

The approach used was to determine the arrival velocity for a given transfer trajectory and initiate burning such that circular orbit conditions are attained at burnout. The equations of motion were

integrated on a RECOMP II computer, using a Runge-Kutta numerical integration procedure.

SECTION II. ASSUMPTIONS

The following is a summary of the basic assumptions used in this study:

1. Deceleration of a single stage from an interplanetary transfer trajectory to a 600-km circular Martian orbit, using a constant thrust directed against the velocity vector.

2. Constant specific impulse values:

   a. 400 sec

   b. 425 sec

   c. 450 sec

   d. 475 sec

   e. 500 sec

3. The earth thrust-to-weight ratio for a chemical stage was varied parametrically from 0.2 to 1.0.

4. Mean spherical planet Mars:

   $\mu = 42930.0 \text{ km}^3/\text{sec}^2$

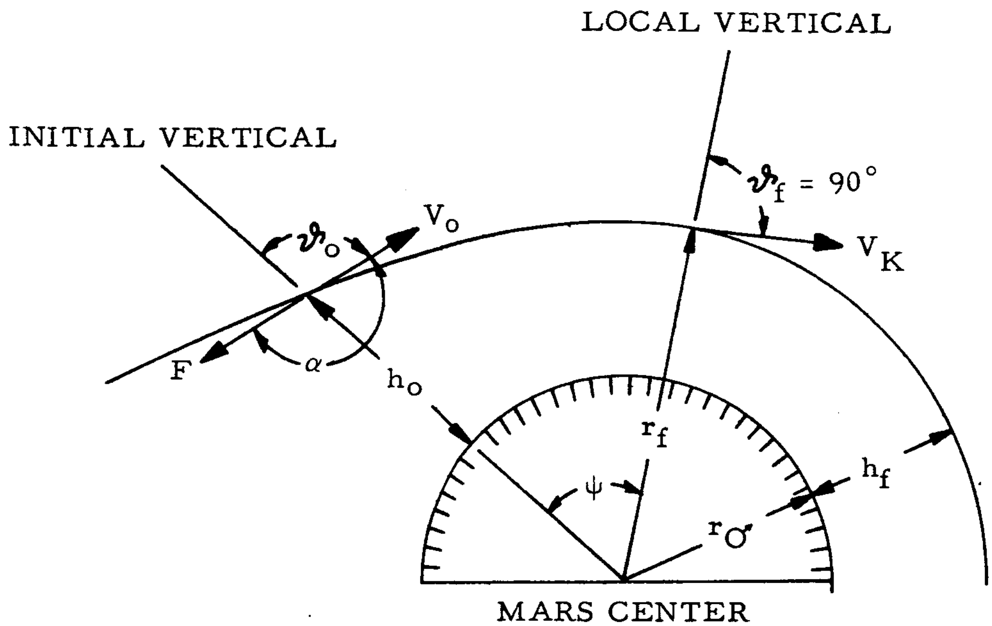
   $r = 3400.0 \text{ km}$

SECTION III. ANALYSIS

In Martian mission programs, it is assumed that one mode of flight will be by way of a transfer from a circular orbit around Mars. In general, a spacecraft will approach the vicinity of Mars with a relative hyperbolic flight velocity.

The velocity requirements for injection into a 600-km circular orbit from an interplanetary transfer trajectory were calculated using the equations of motion for a vehicle flying into orbit with an angle of attack of 180 degrees.

Referring to the sketch below, computations were made for a point mass moving in a plane using the following equations of motion:



$$\dot{V} = \frac{F \cos \alpha}{m} - \frac{\mu_{♂}}{r^2} \cos \vartheta \tag{1}$$

$$V\dot{\vartheta} = \frac{F \sin \alpha}{m} + \left(\frac{\mu_{♂}}{r^2} - \frac{V^2}{r} \right) \sin \vartheta \tag{2}$$

$$\dot{r} = V \cos \vartheta \tag{3}$$

$$\dot{\psi} = \frac{V \sin \vartheta}{r} \tag{4}$$

where

$$m = m_o + \int \dot{m}\, dt \tag{5}$$

and

$$\dot{m} = - \frac{F}{V_{ex}} \tag{6}$$

The velocity and flight path angle may be obtained by integrating the equation of motion

$$V = V_o + \int \dot{V}\, dt \qquad (7)$$

$$\vartheta = \vartheta_o + \int \dot{\vartheta}\, dt \qquad (8)$$

The range and pericenter altitude can then be calculated by the relations

$$X = X_o + \int \frac{r_{♂}}{r} V \sin \vartheta \, dt \qquad (9)$$

$$h = h_o + \int \dot{r}\, dt \qquad (10)$$

and the central angle is

$$\psi = \psi_o + \int \frac{\dot{X}}{r_{♂}} dt \qquad (11)$$

The initial weight of the vehicle is

$$W_o = W_C + W_P \qquad (12)$$

The velocity expended by a vehicle is the characteristic velocity, or

$$V_1 = V_{ex} \ln \frac{1}{1 - \zeta} \qquad (13)$$

Then the velocity losses are the difference between the characteristic velocity and the change in comparative velocity, or

$$V_{loss} = V_1 - \Delta V^* \qquad (14)$$

where the comparative velocity is

$$V^* = \sqrt{V^2 + 2\mu_{♂} \left(\frac{1}{r} - \frac{1}{r_{♂}} \right)} \qquad (15)$$

The change in comparative velocity during descent from $r = r_o$ to $r = r_f$ is

$$\Delta V^* = \sqrt{V_o^2 + 2\mu_{♂} \left(\frac{1}{r_f} - \frac{1}{r_o}\right)} - V_f \tag{16}$$

and the velocity loss due to gravity is

$$V_{loss} = V_{ex} \ln \left(\frac{1}{1 - \zeta}\right) - \left[\sqrt{V_o^2 + 2\mu_{♂} \left(\frac{1}{r_f} - \frac{1}{r_o}\right)} - V_f\right] \tag{17}$$

SECTION IV. DISCUSSION OF RESULTS

The results of this investigation are shown in Figures 1 through 13. The characteristic velocity, V_1, is plotted versus hyperbolic excess velocity with earth thrust-to-weight ratios as a parameter in Figures 1 through 5.

Figures 6 and 7 show the velocity losses due to gravity for specific impulse values of 400 sec and 500 sec respectively. These losses tend to zero as the thrust-to-weight ratio is increased. The flight path angle at initiation of burning prior to Keplerian pericenter is shown in Figure 8.

Figure 9 shows the change in altitude. This change is the difference between the altitude at initiation of burning and the altitude of the circular orbit about Mars. The change in other trajectory parameters is shown in Figures 10 and 11. The vehicle mass characteristics can be determined from Figures 12 and 13.

SECTION V. CONCLUSIONS

From this parametric analysis, sufficient data are presented to enable the designer to make a preliminary design of a stage for braking into an orbit about the planet Mars when the mission requirements are defined.

SECTION VI. GRAPHIC PRESENTATION

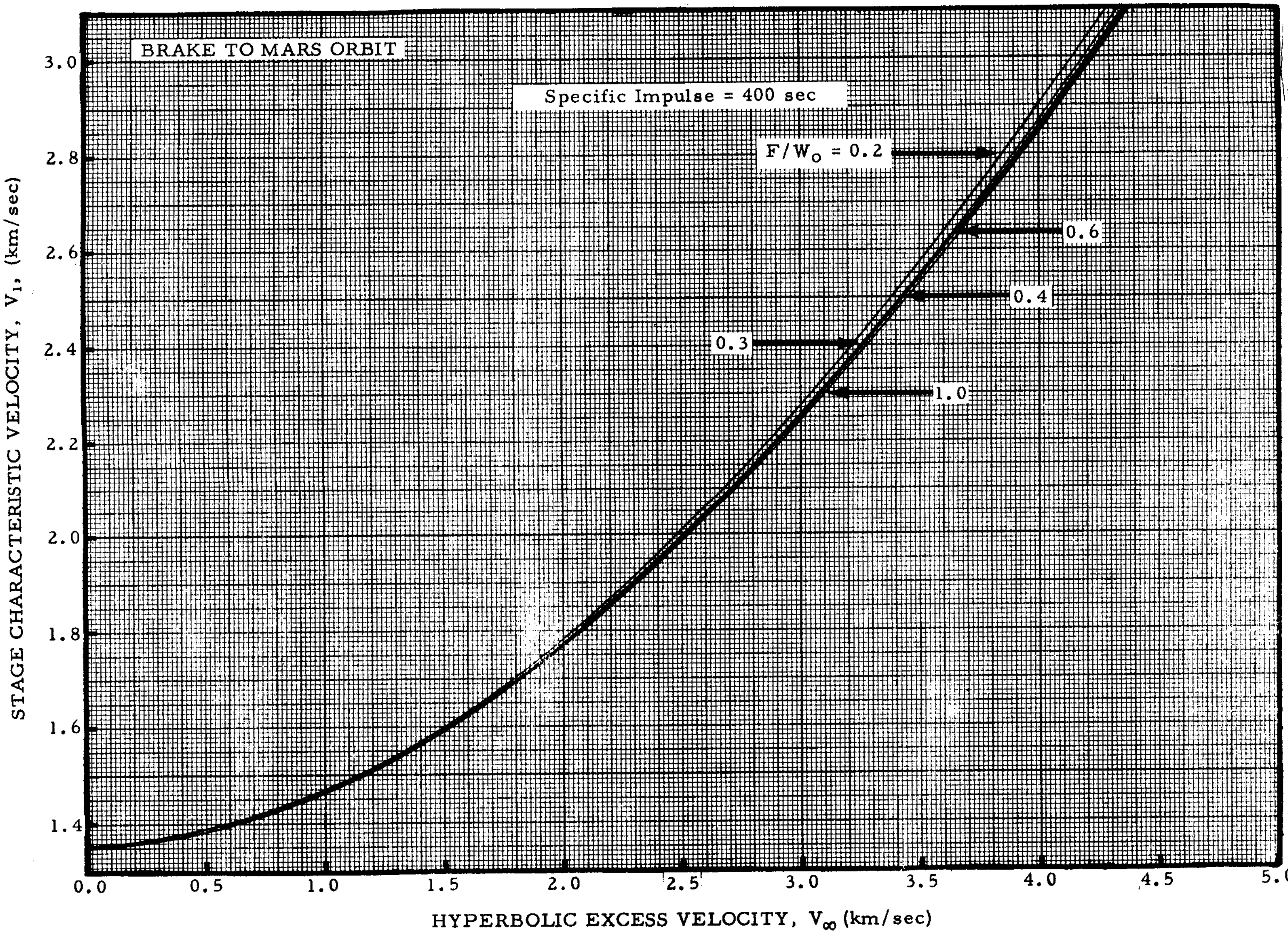


FIGURE 1a. CHARACTERISTIC VELOCITY, V_1 (km/sec), VERSUS HYPERBOLIC EXCESS VELOCITY, V_∞ (km/sec), WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER FOR A CONSTANT SPECIFIC IMPULSE OF 400 SECONDS

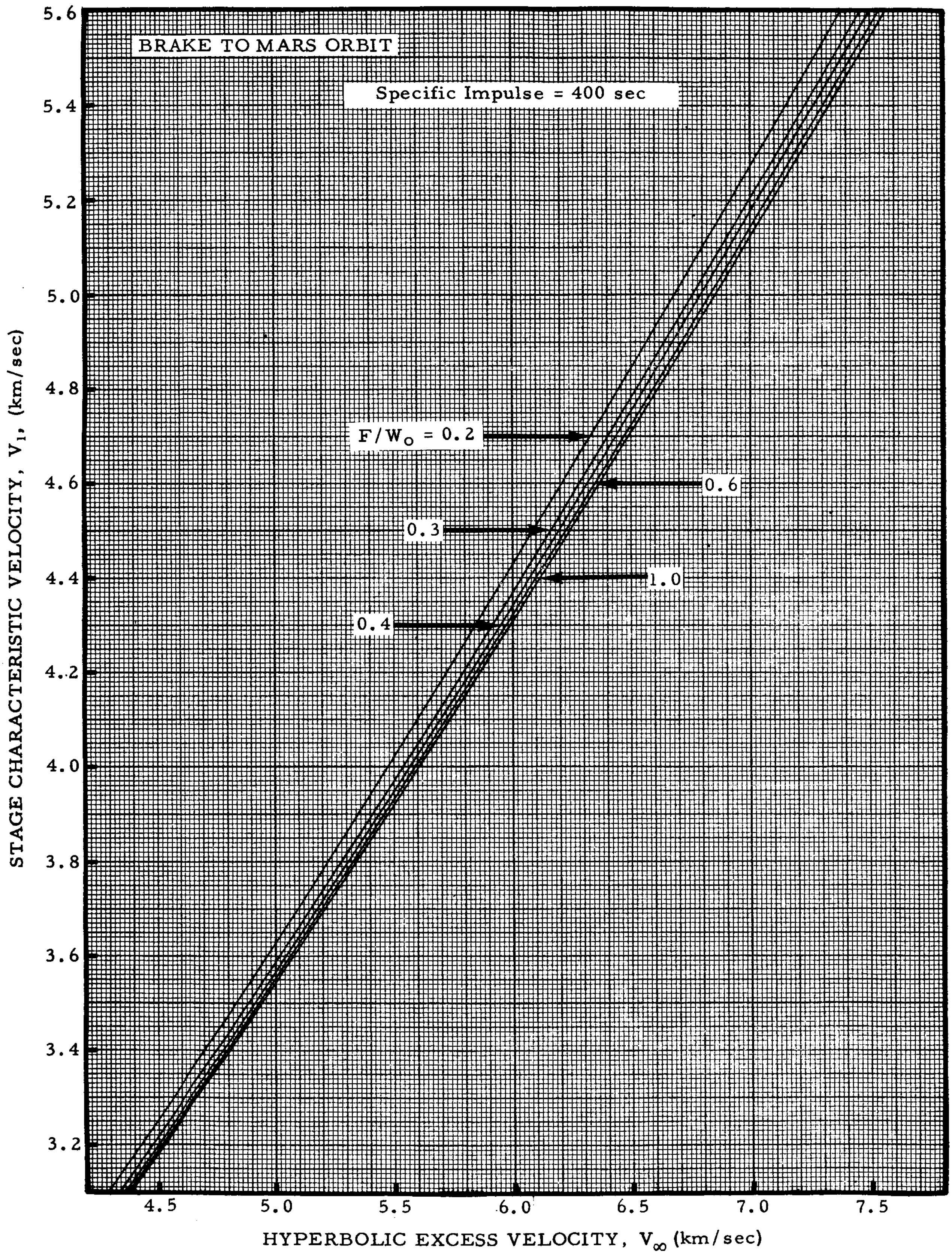


FIGURE 1b. CHARACTERISTIC VELOCITY, V_1 (km/sec), VERSUS HYPERBOLIC EXCESS VELOCITY, V_∞ (km/sec), WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER FOR A CONSTANT SPECIFIC IMPULSE OF 400 SECONDS

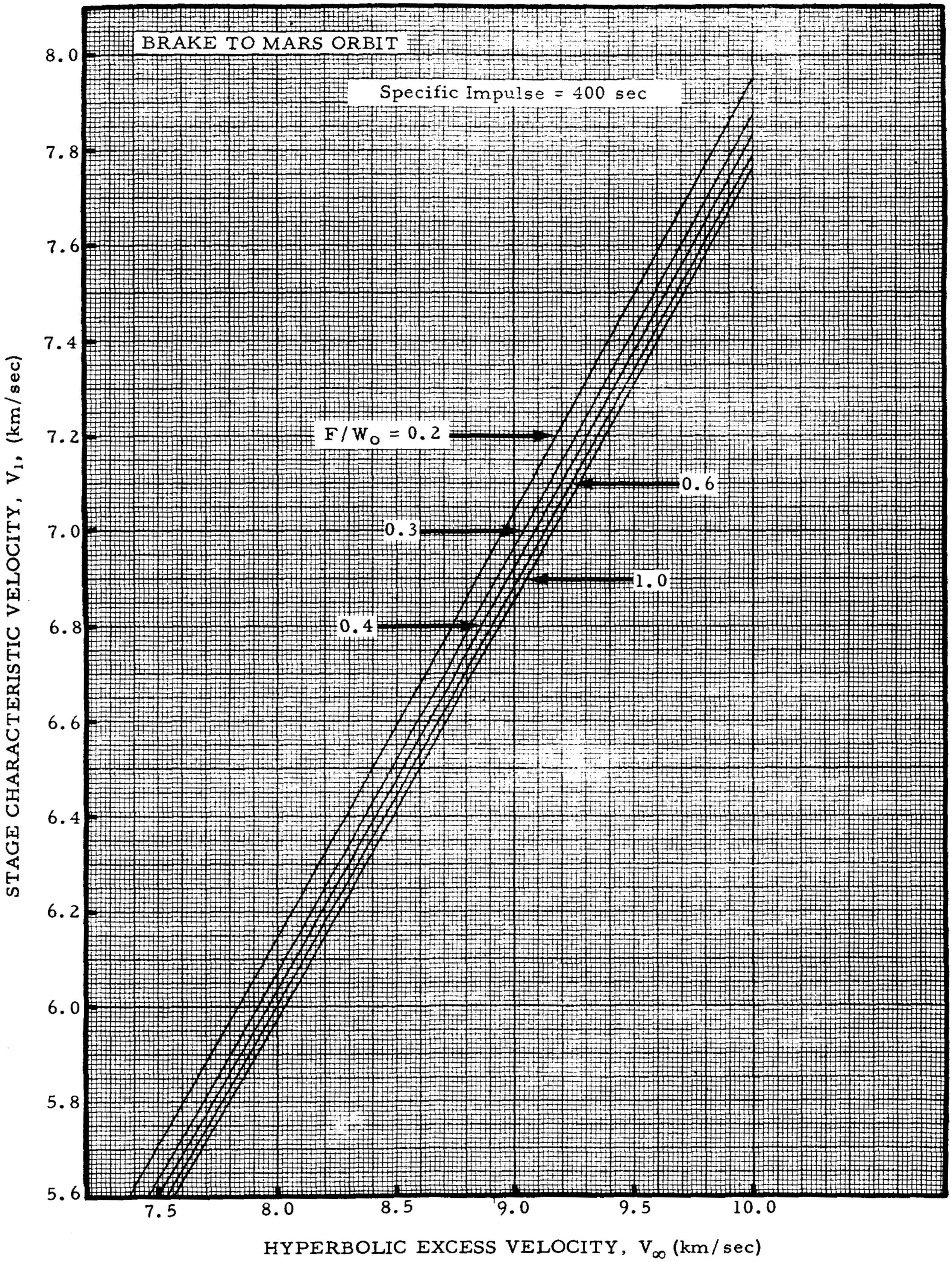


FIGURE 1c. CHARACTERISTIC VELOCITY, V_1 (km/sec), VERSUS HYPERBOLIC EXCESS VELOCITY, V_∞ (km/sec), WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER FOR A CONSTANT SPECIFIC IMPULSE OF 400 SECONDS

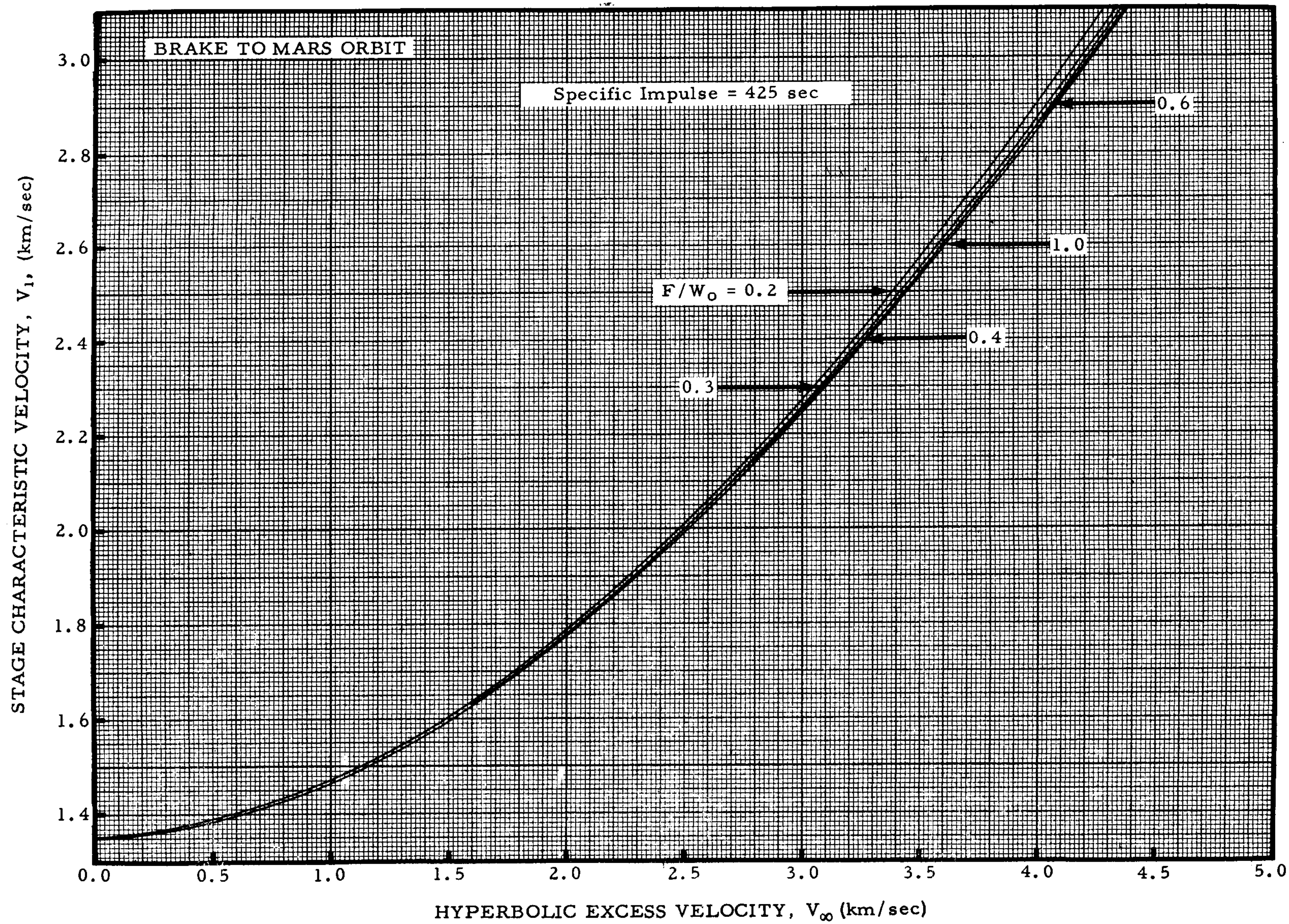


FIGURE 2a. CHARACTERISTIC VELOCITY, V_1 (km/sec), VERSUS HYPERBOLIC EXCESS VELOCITY, V_∞ (km/sec), WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER FOR A CONSTANT SPECIFIC IMPULSE OF 425 SECONDS

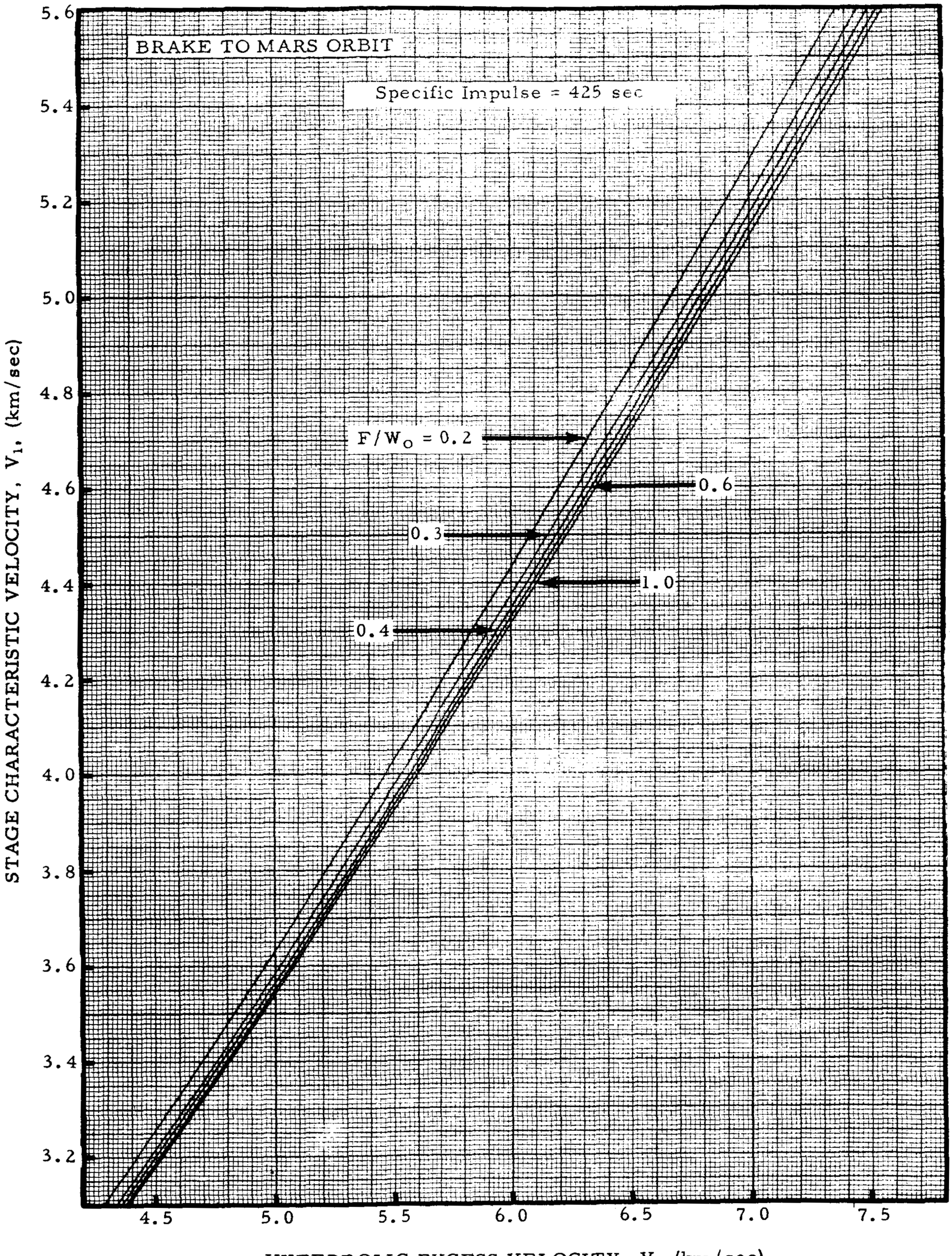


FIGURE 2b. CHARACTERISTIC VELOCITY, V_1 (km/sec), VERSUS HYPERBOLIC EXCESS VELOCITY, V_∞ (km/sec), WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER FOR A CONSTANT SPECIFIC IMPULSE OF 425 SECONDS

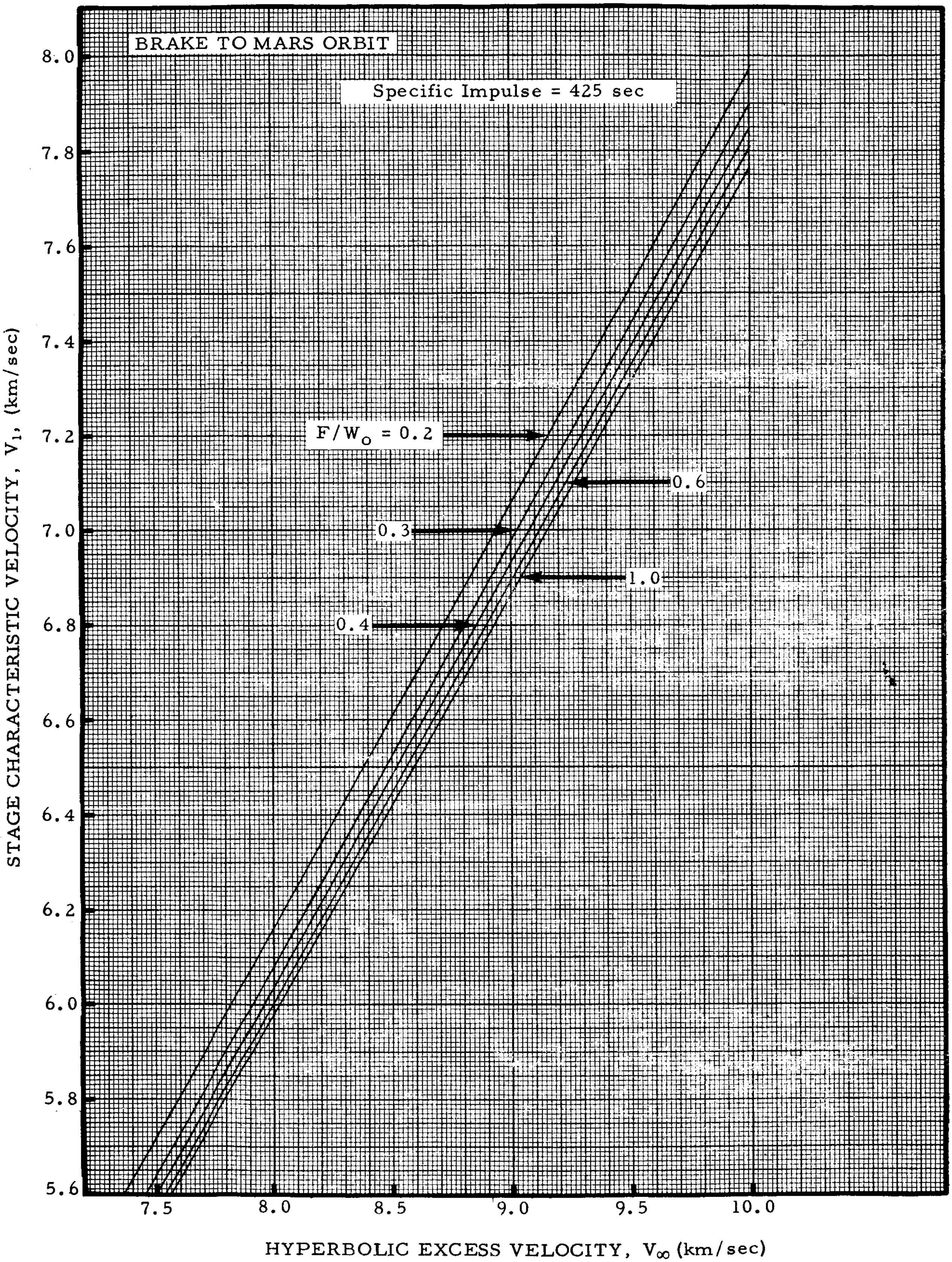


FIGURE 2c. CHARACTERISTIC VELOCITY, V_1 (km/sec), VERSUS HYPERBOLIC EXCESS VELOCITY, V_∞ (km/sec), WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER FOR A CONSTANT SPECIFIC IMPULSE OF 425 SECONDS

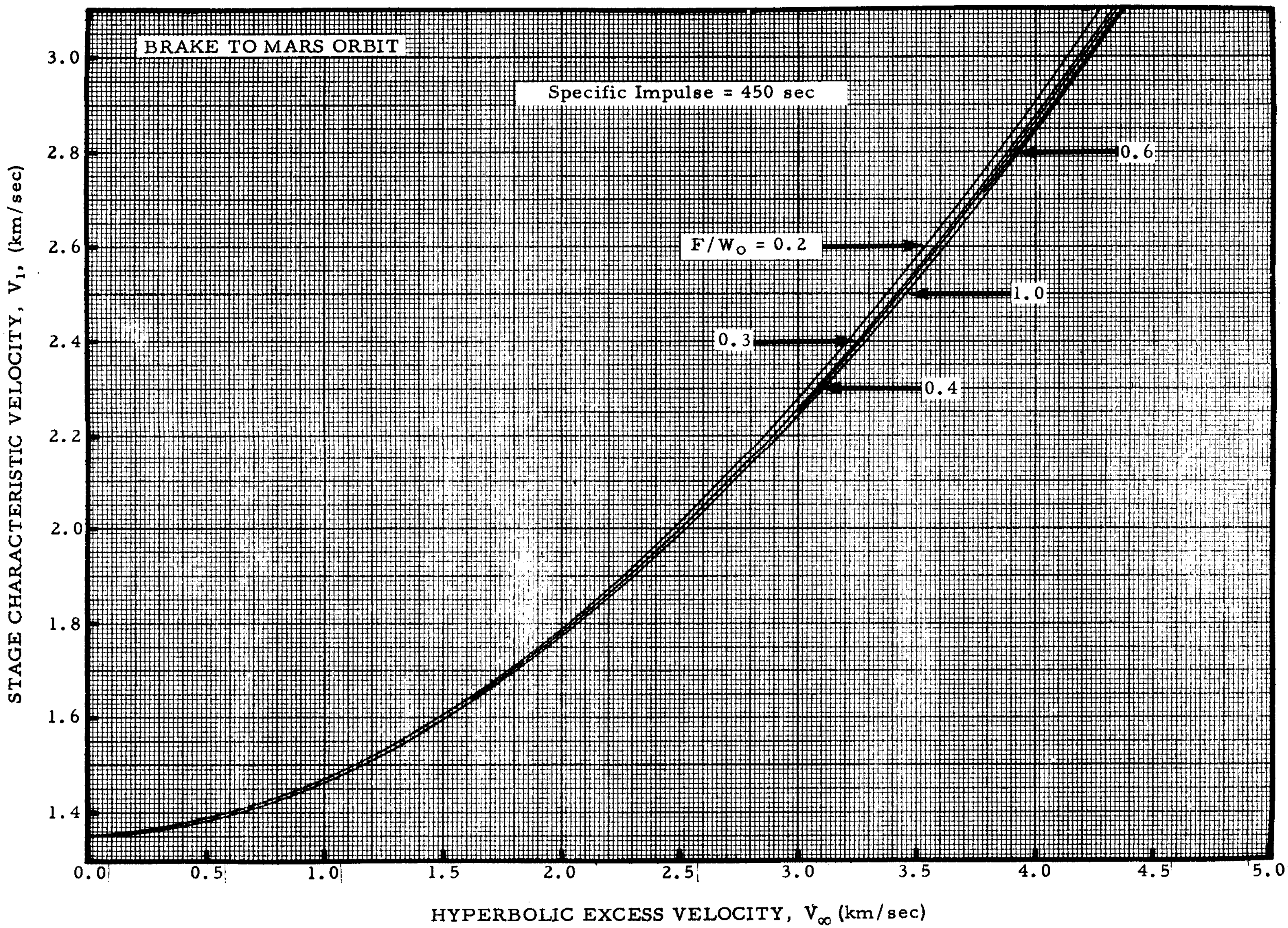


FIGURE 3a. CHARACTERISTIC VELOCITY, V_1 (km/sec), VERSUS HYPERBOLIC EXCESS VELOCITY, V_∞ (km/sec), WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER FOR A CONSTANT SPECIFIC IMPULSE OF 450 SECONDS

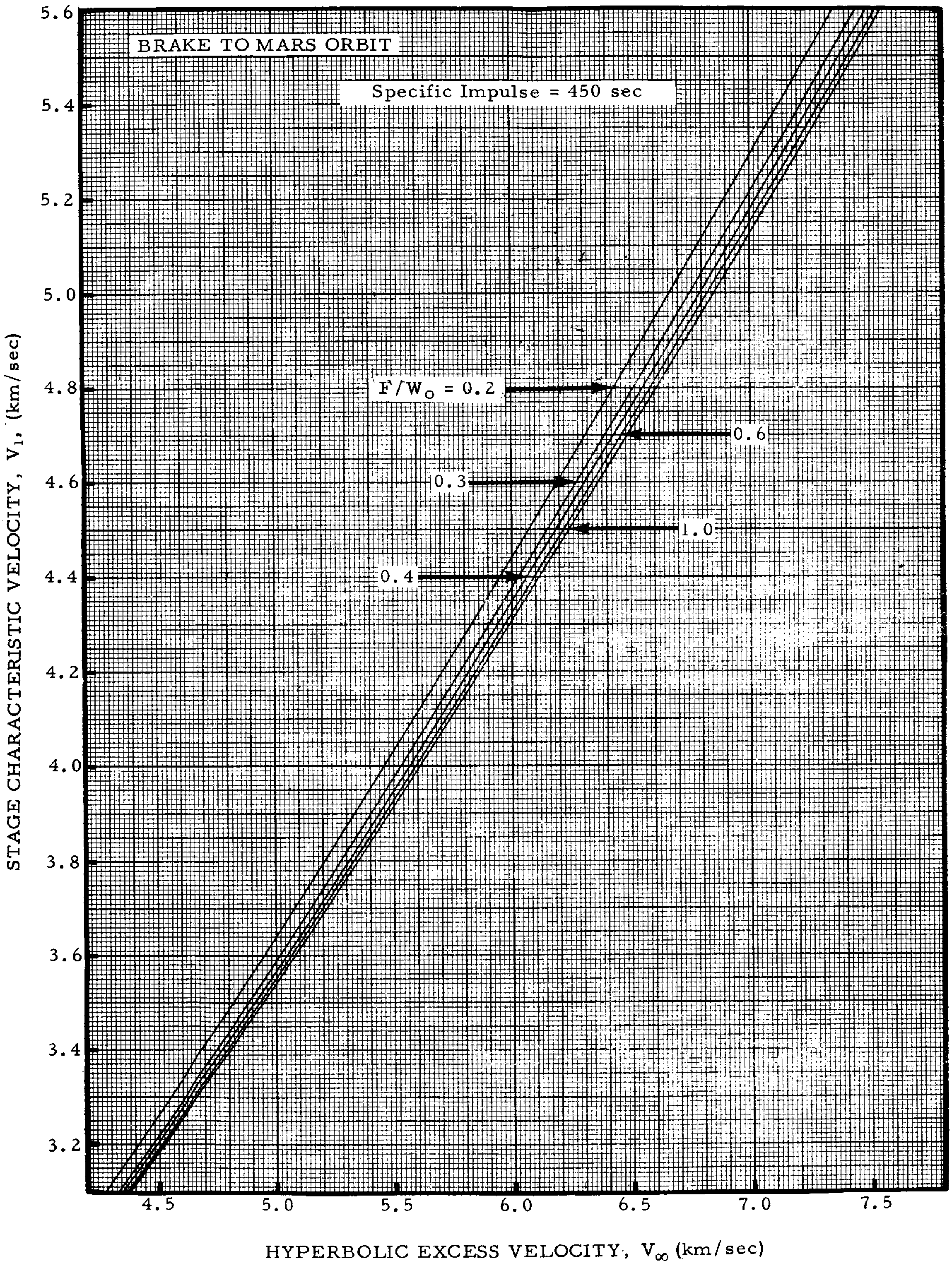


FIGURE 3b. CHARACTERISTIC VELOCITY, V_1 (km/sec), VERSUS HYPERBOLIC EXCESS VELOCITY, V_∞ (km/sec), WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER FOR A CONSTANT SPECIFIC IMPULSE OF 450 SECONDS

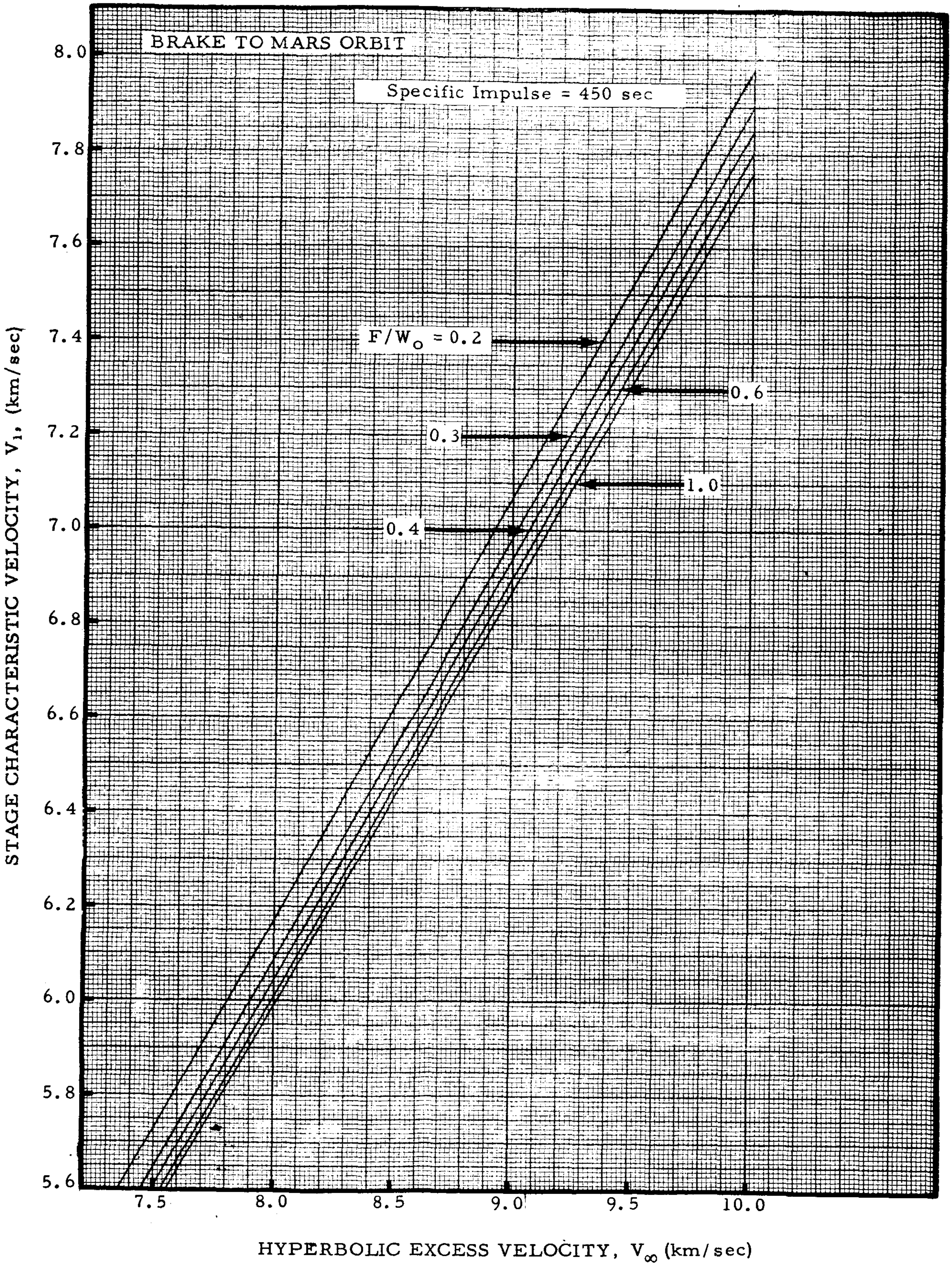


FIGURE 3c. CHARACTERISTIC VELOCITY, V_1 (km/sec), VERSUS HYPERBOLIC EXCESS VELOCITY, V_∞ (km/sec), WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER FOR A CONSTANT SPECIFIC IMPULSE OF 450 SECONDS

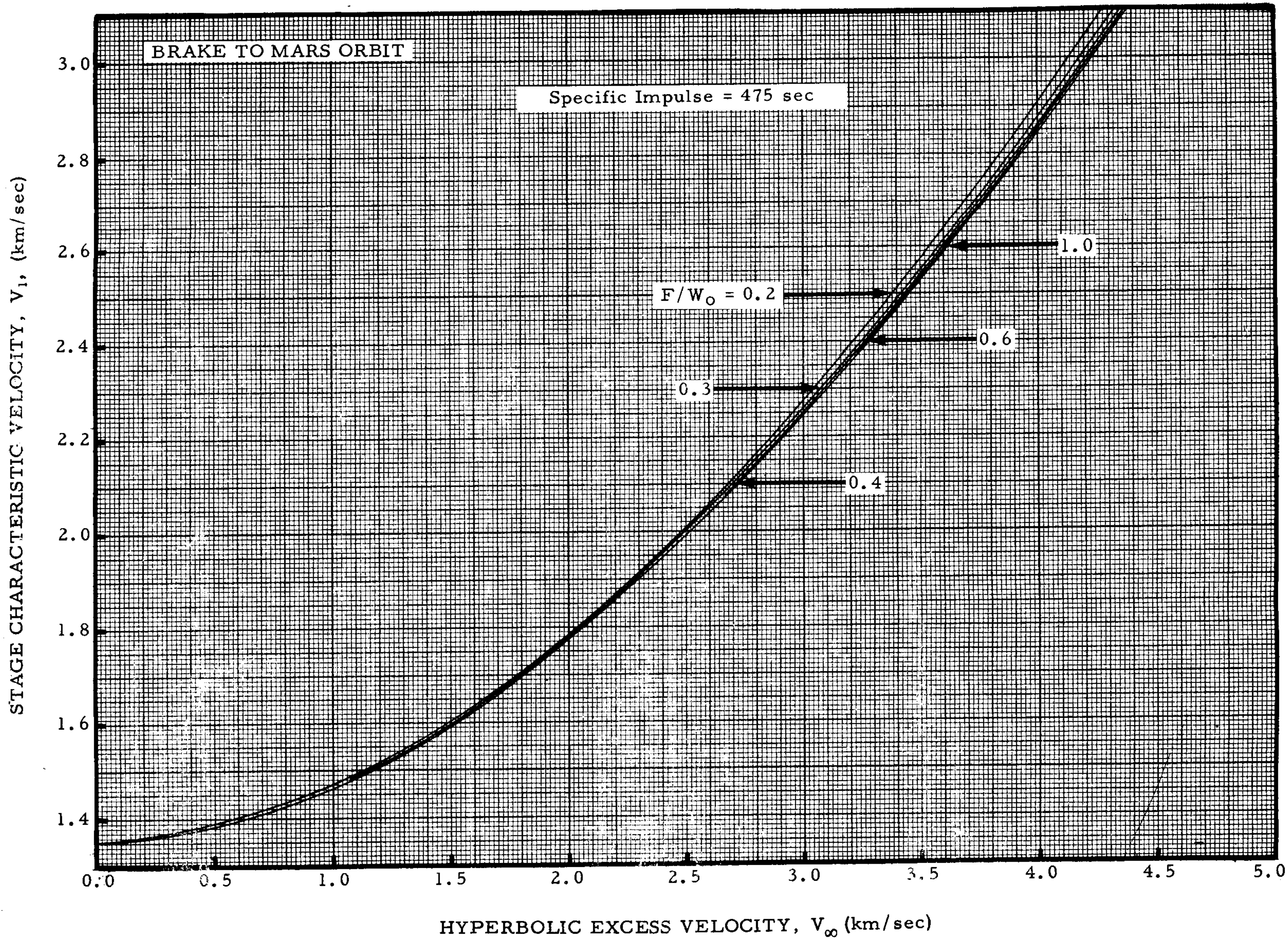


FIGURE 4a. CHARACTERISTIC VELOCITY, V_1 (km/sec), VERSUS HYPERBOLIC EXCESS VELOCITY, V_∞ (km/sec), WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER FOR A CONSTANT SPECIFIC IMPULSE OF 475 SECONDS

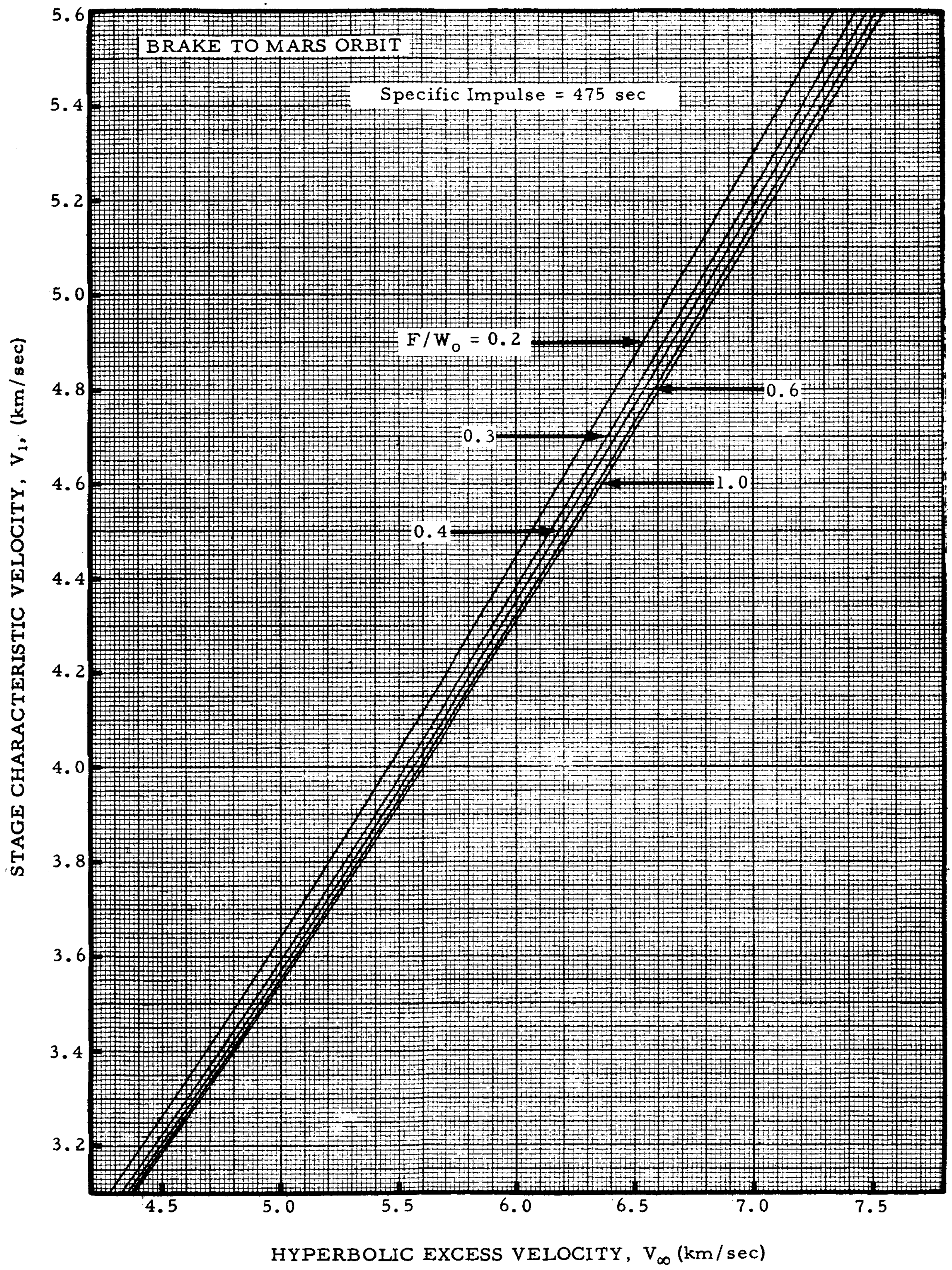


FIGURE 4b. CHARACTERISTIC VELOCITY, V_1 (km/sec), VERSUS HYPERBOLIC EXCESS VELOCITY, V_∞ (km/sec), WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER FOR A CONSTANT SPECIFIC IMPULSE OF 475 SECONDS

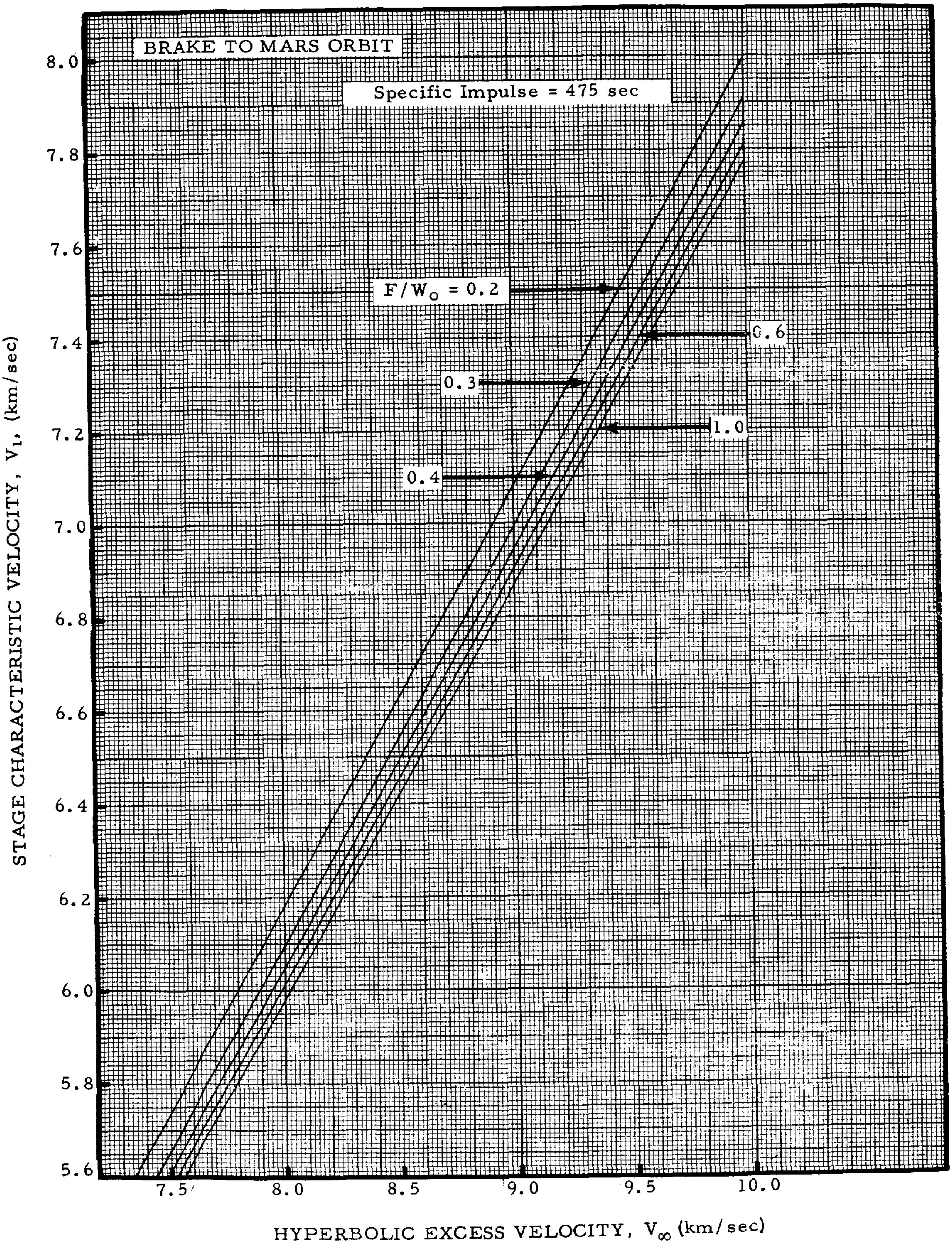


FIGURE 4c. CHARACTERISTIC VELOCITY, V_1 (km/sec), VERSUS HYPERBOLIC EXCESS VELOCITY, V_∞ (km/sec), WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER FOR A CONSTANT SPECIFIC IMPULSE OF 475 SECONDS

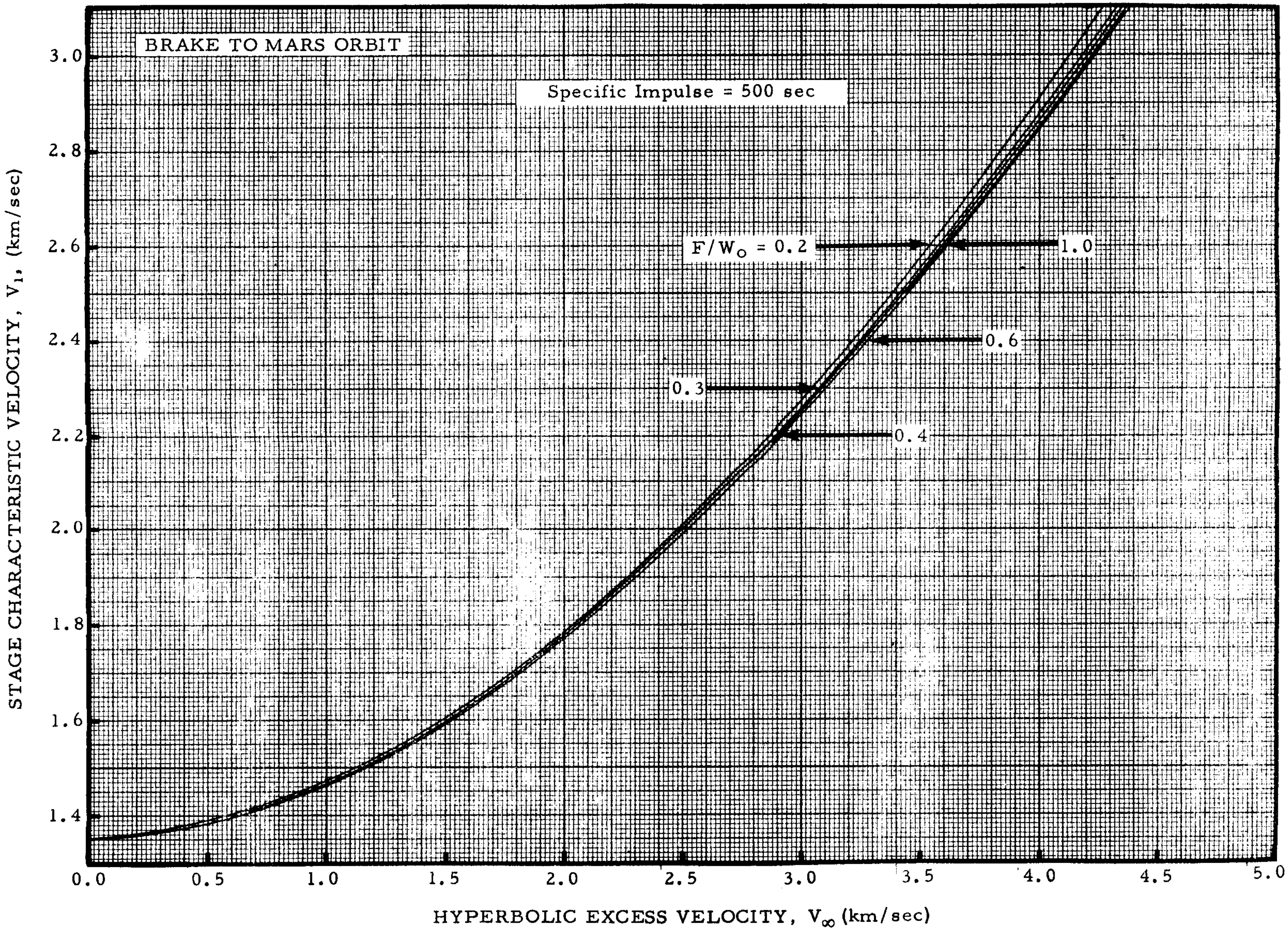


FIGURE 5a. CHARACTERISTIC VELOCITY, V_1 (km/sec), VERSUS HYPERBOLIC EXCESS VELOCITY, V_∞ (km/sec), WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER FOR A CONSTANT SPECIFIC IMPULSE OF 500 SECONDS

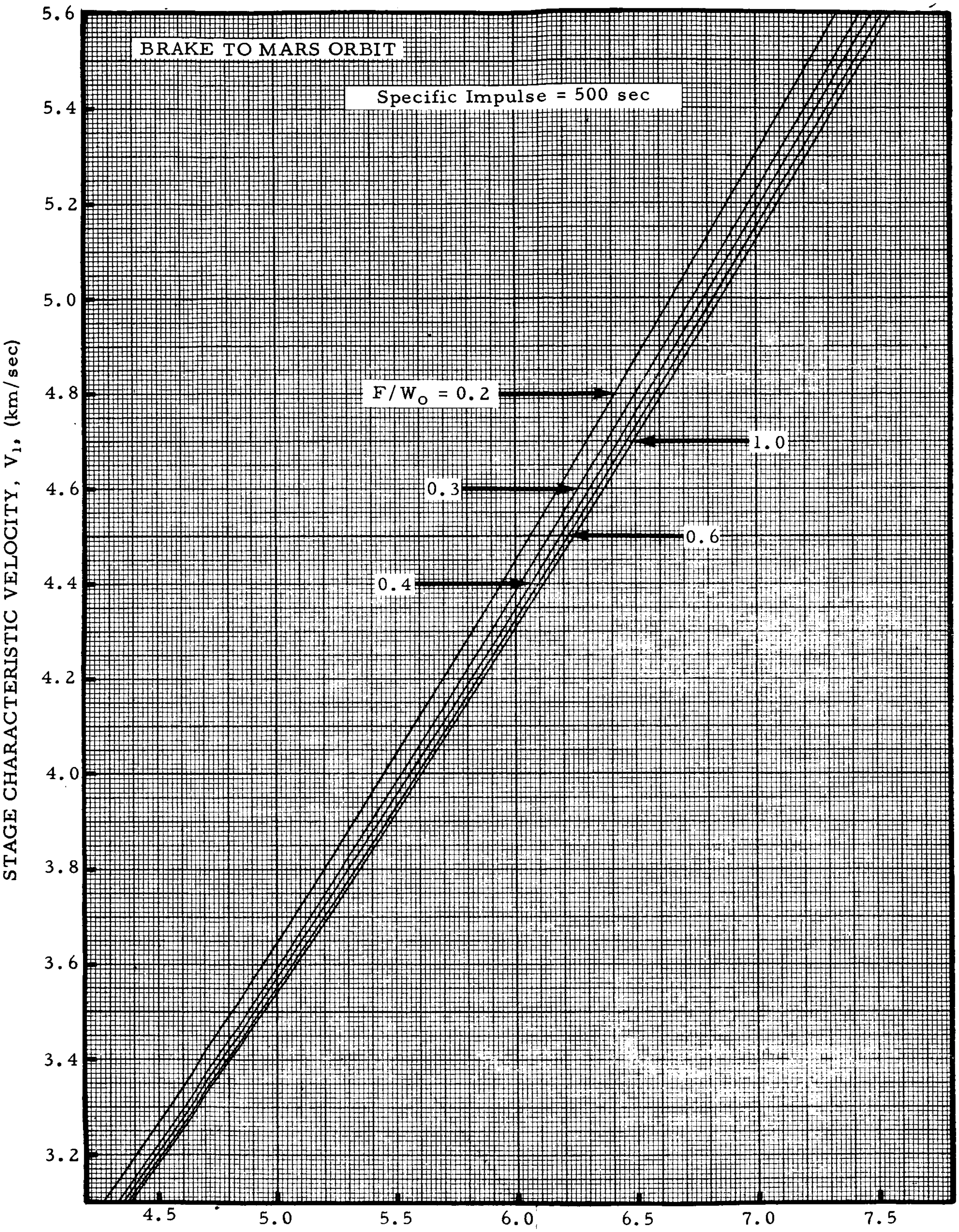


FIGURE 5b. CHARACTERISTIC VELOCITY, V_1 (km/sec), VERSUS HYPERBOLIC EXCESS VELOCITY, V_∞ (km/sec), WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER FOR A CONSTANT SPECIFIC IMPULSE OF 500 SECONDS

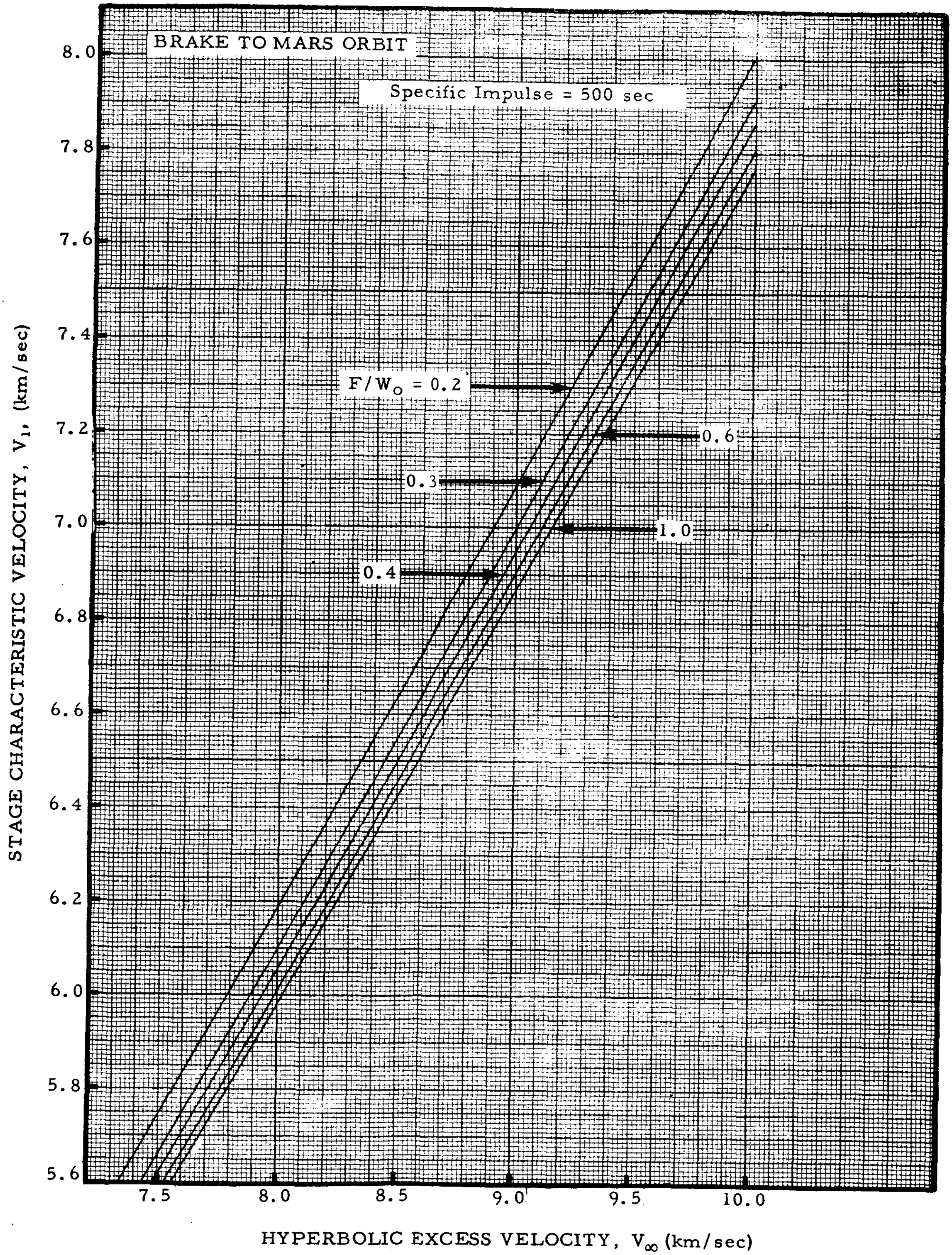


FIGURE 5c. CHARACTERISTIC VELOCITY, V_1 (km/sec), VERSUS HYPERBOLIC EXCESS VELOCITY, V_∞ (km/sec), WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER FOR A CONSTANT SPECIFIC IMPULSE OF 500 SECONDS

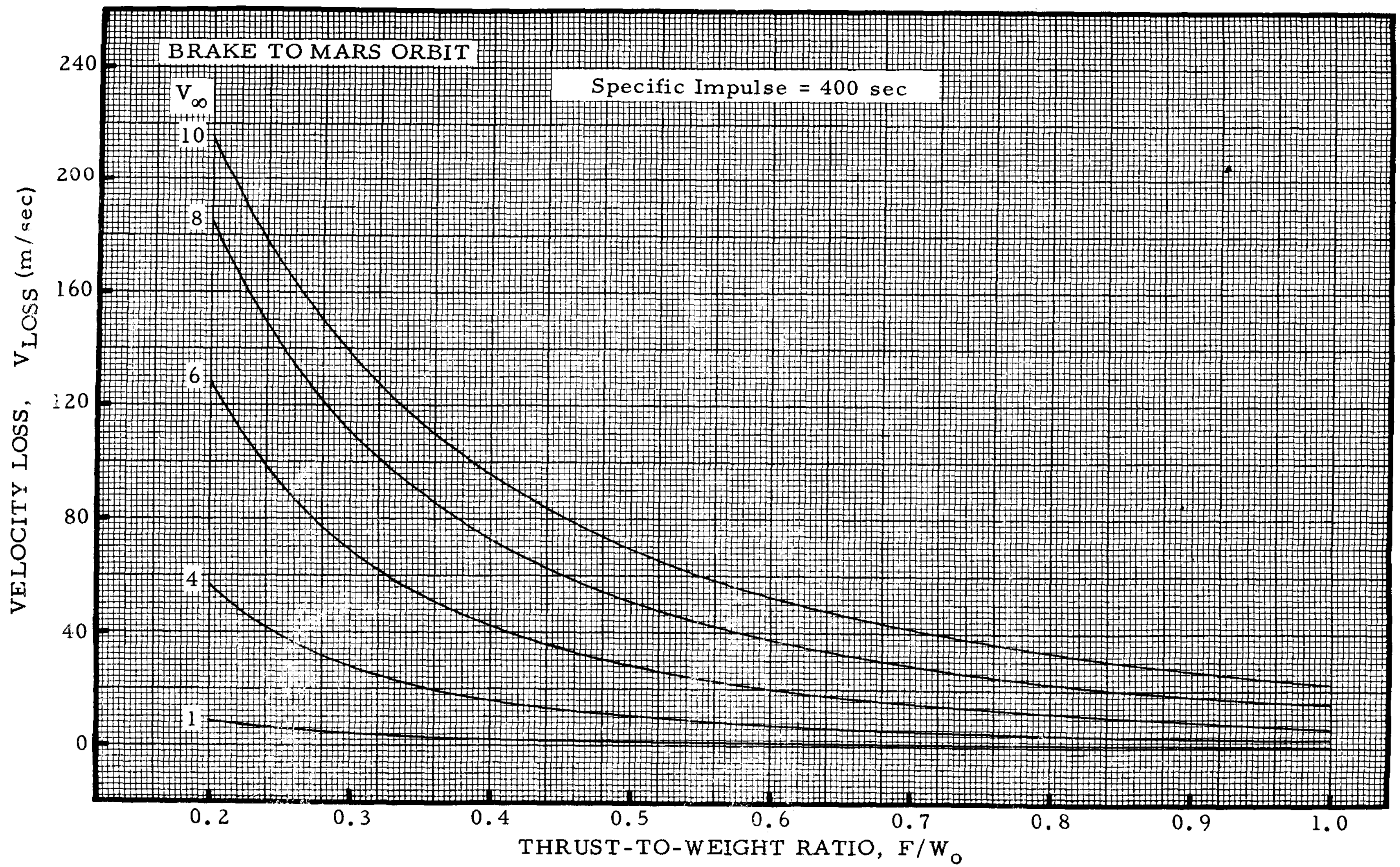


FIGURE 6. VELOCITY LOSS (m/sec) DUE TO GRAVITY VERSUS THRUST-TO-WEIGHT RATIO WITH HYPERBOLIC EXCESS VELOCITY (km/sec) AS A PARAMETER

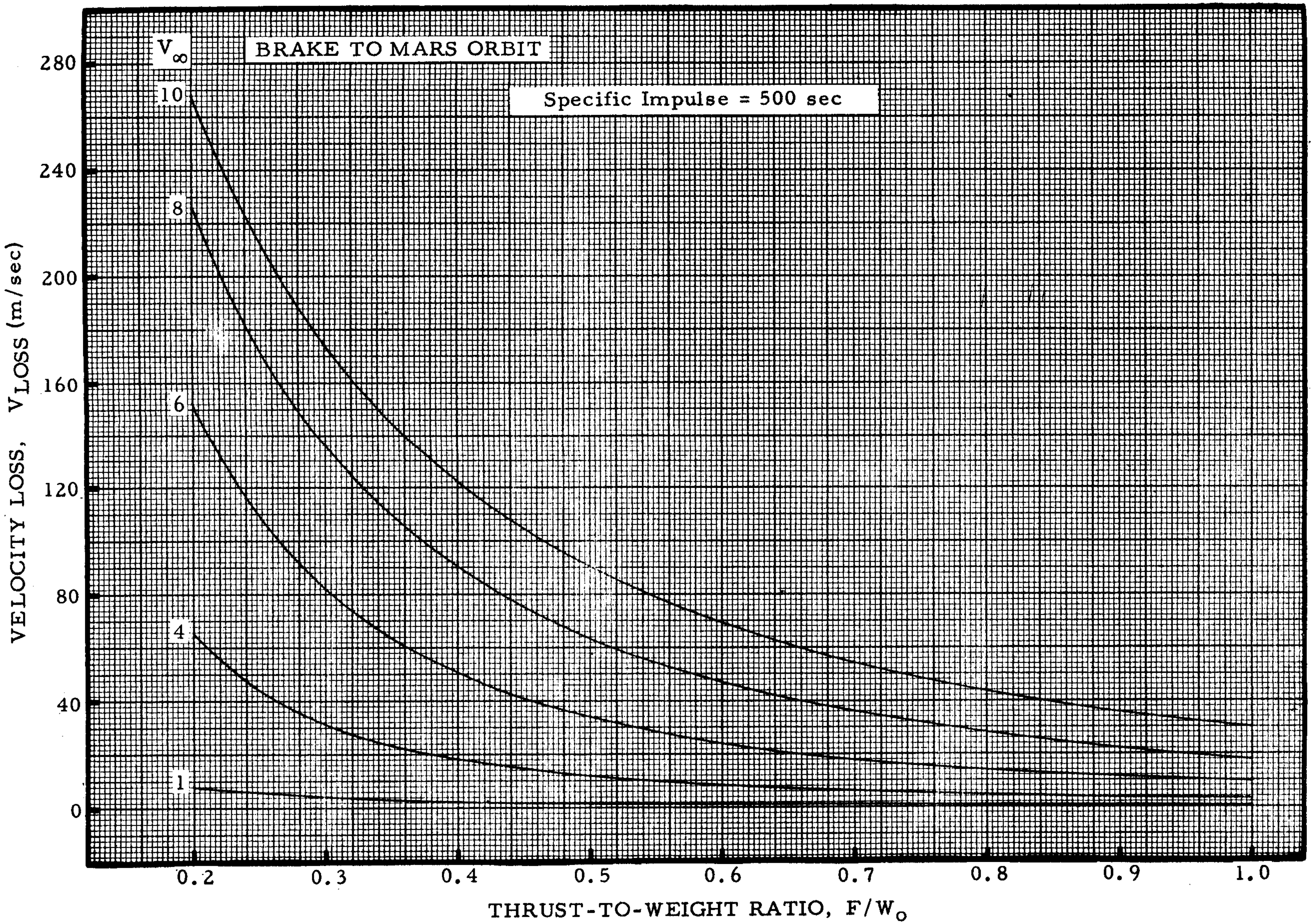


FIGURE 7. VELOCITY LOSS (m/sec) DUE TO GRAVITY VERSUS THRUST-TO-WEIGHT RATIO WITH HYPERBOLIC EXCESS VELOCITY (km/sec) AS A PARAMETER

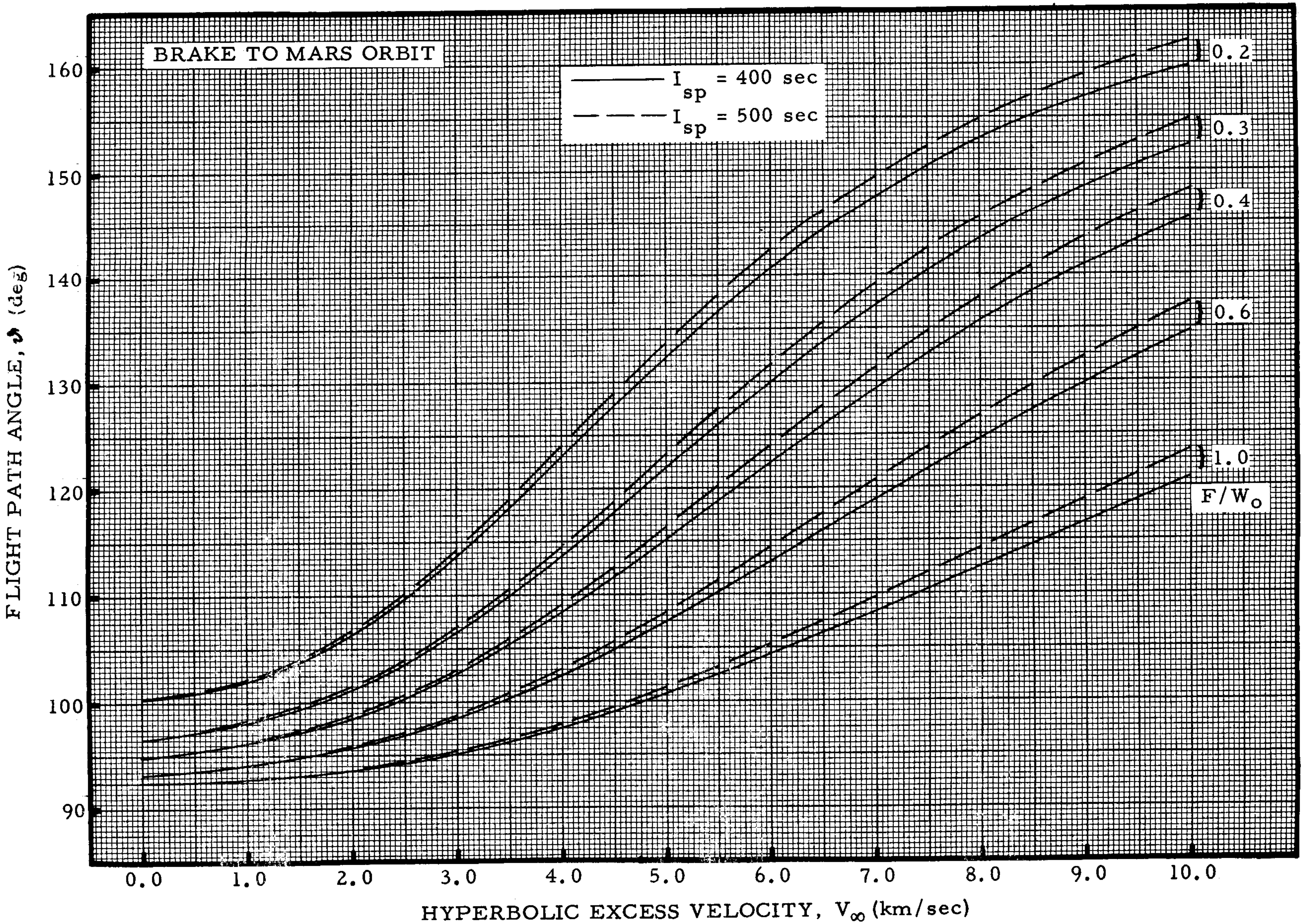


FIGURE 8. FLIGHT PATH ANGLE (deg) VERSUS HYPERBOLIC EXCESS VELOCITY (km/sec) WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER

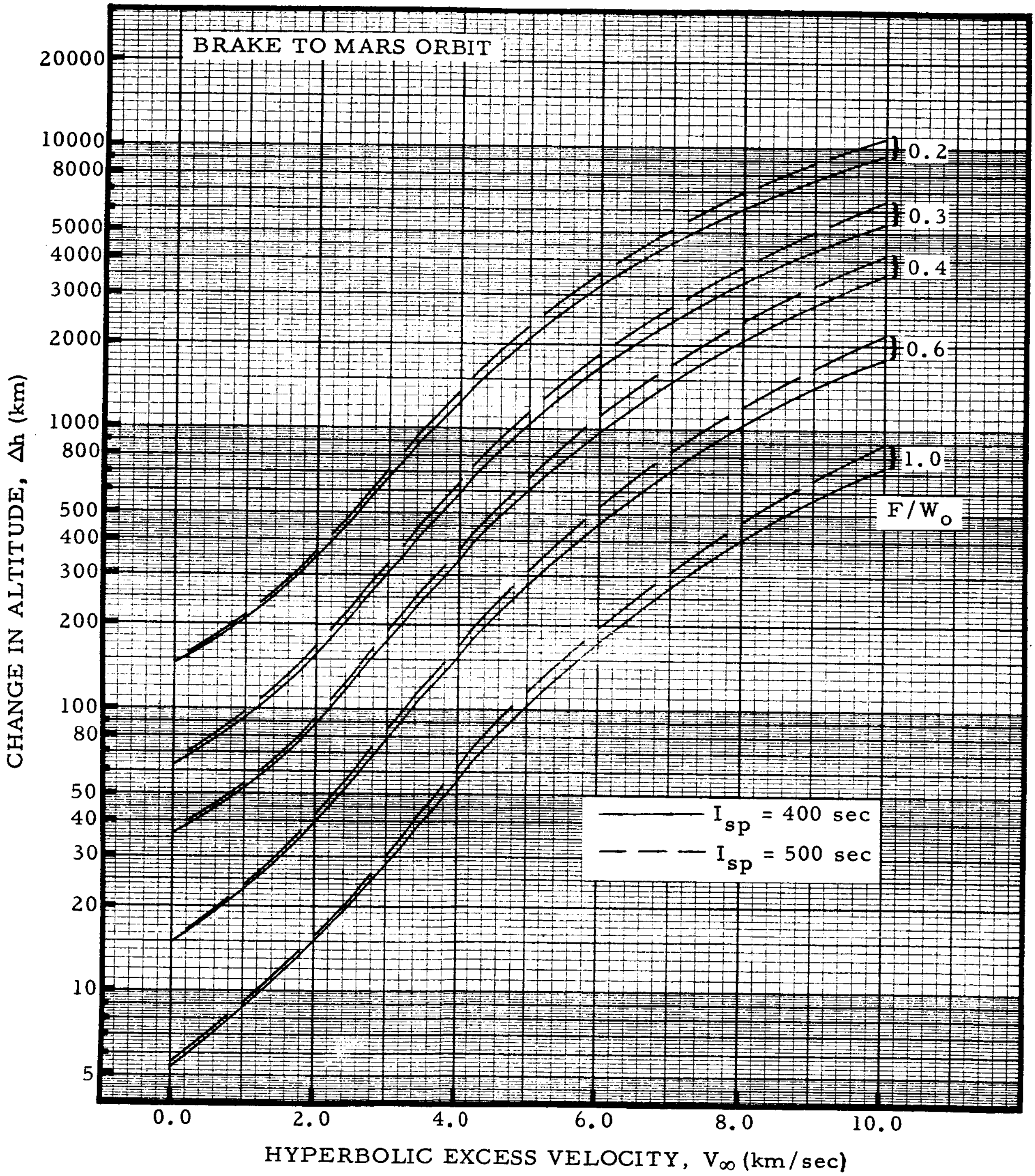


FIGURE 9. CHANGE IN ALTITUDE (km) VERSUS HYPERBOLIC EXCESS VELOCITY (km/sec) WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER

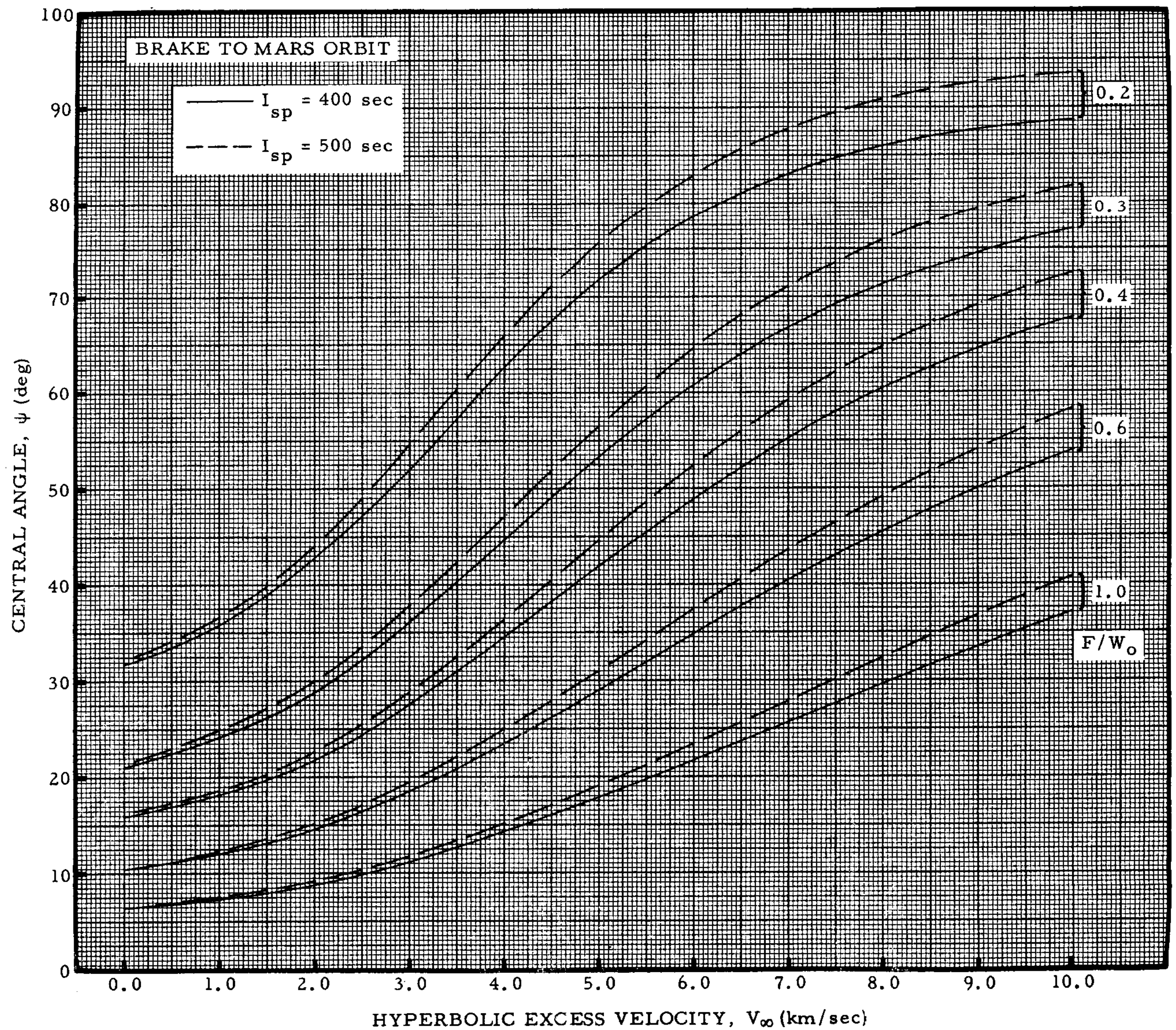


FIGURE 10. CENTRAL ANGLE (deg) VERSUS HYPERBOLIC EXCESS VELOCITY (km/sec) WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER

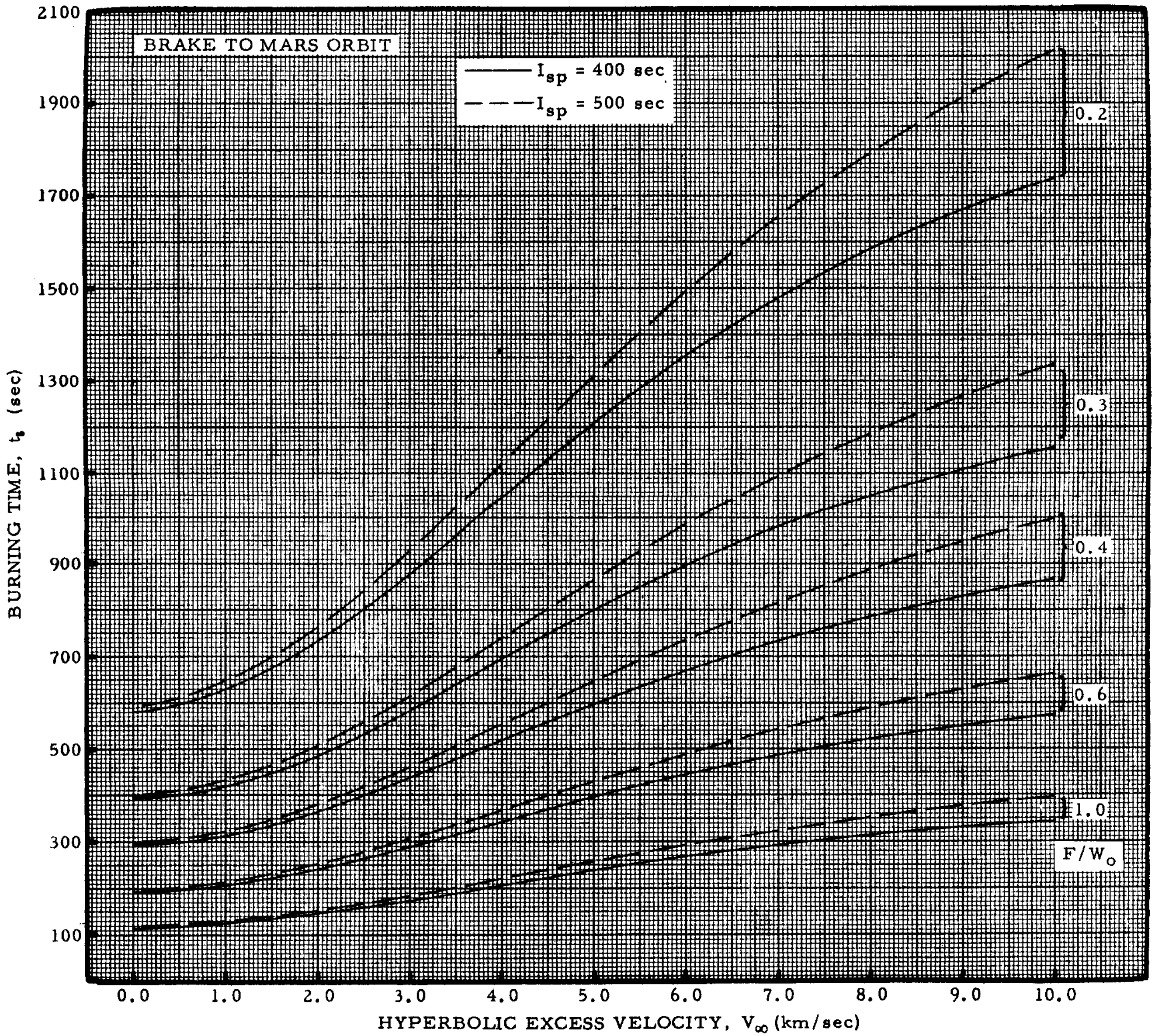


FIGURE 11. BURNING TIME (sec) VERSUS HYPERBOLIC EXCESS VELOCITY (km/sec) WITH THRUST-TO-WEIGHT RATIO AS A PARAMETER

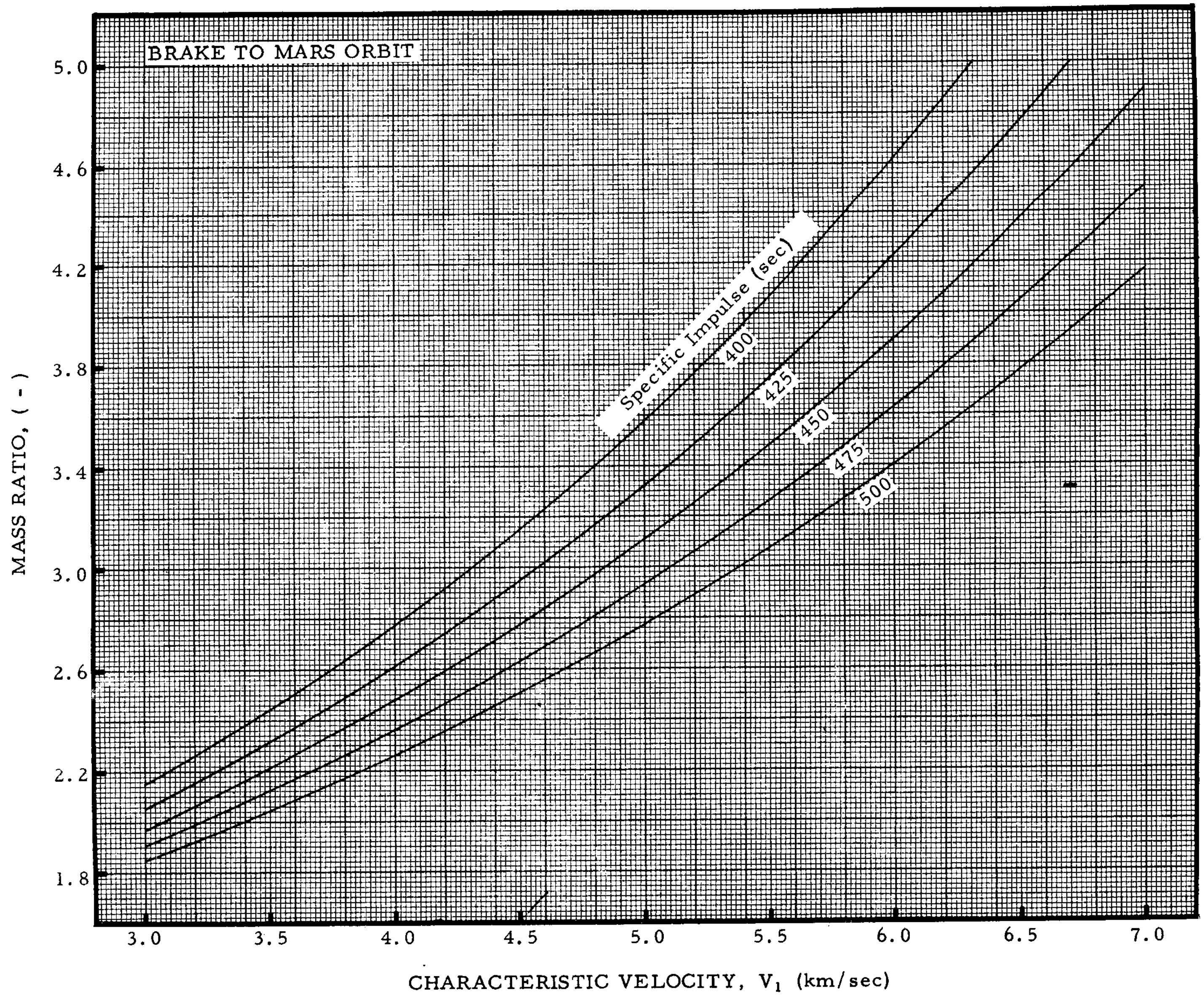


FIGURE 12. MASS RATIO VERSUS CHARACTERISTIC VELOCITY (km/sec) WITH SPECIFIC IMPULSE AS A PARAMETER

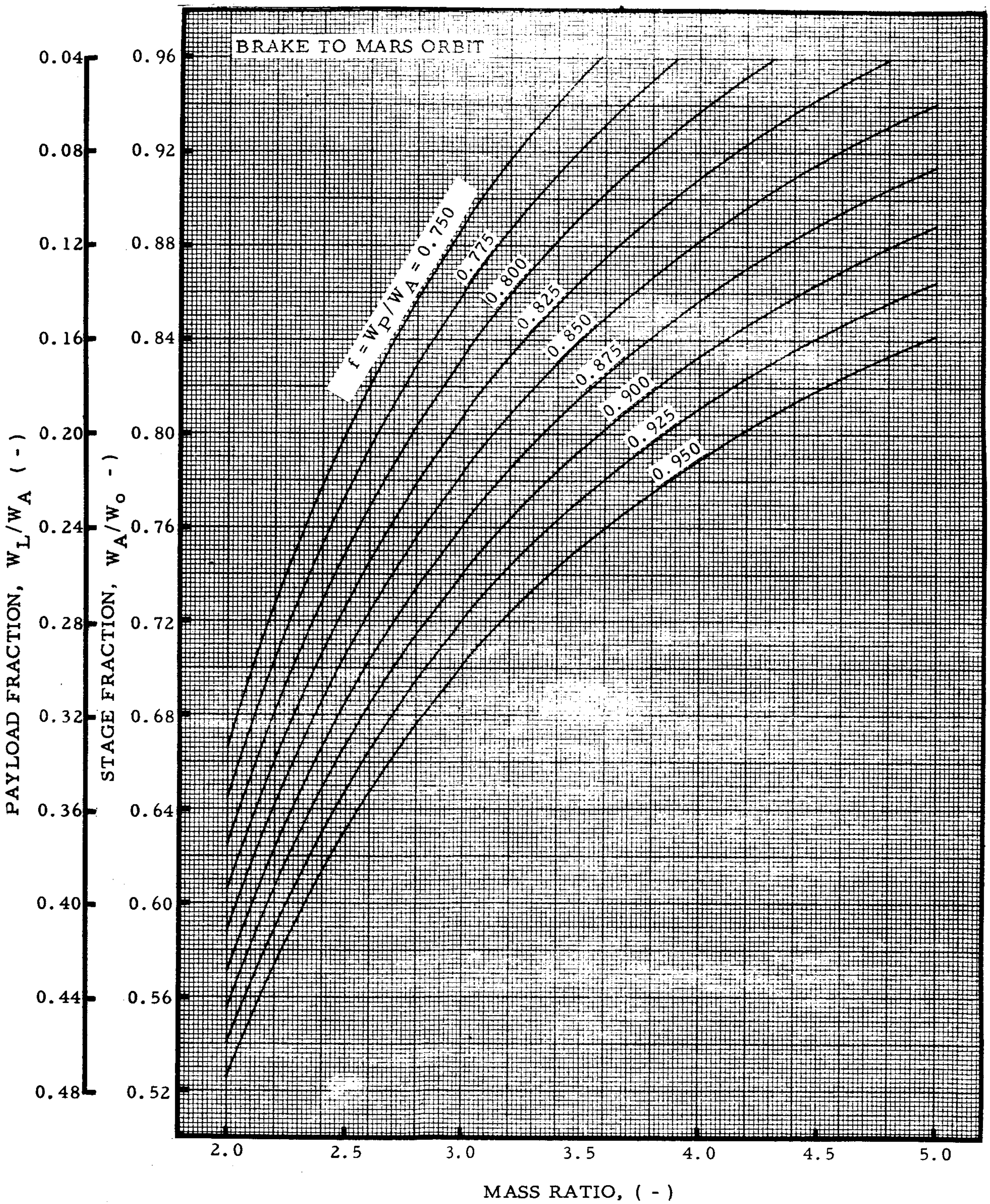


FIGURE 13. PAYLOAD FRACTION AND STAGE FRACTION VERSUS MASS RATIO WITH STAGE MASS FRACTION AS A PARAMETER

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PART III

BRAKE TO MARS ORBIT

By Walter H. Stafford and Carmen R. Catalfamo

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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